

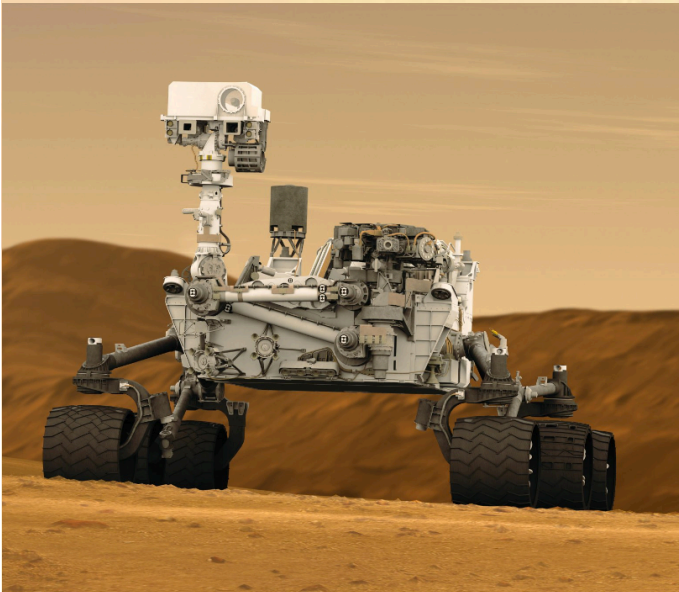


Mars Science Laboratory
Entry Descent & Landing Instrumentation (MEDLI)

Mars Entry Atmospheric Data
System (MEADS)
Overview of Calibration,
Uncertainties & Reconstruction

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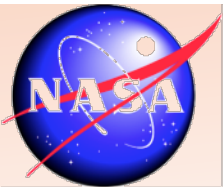




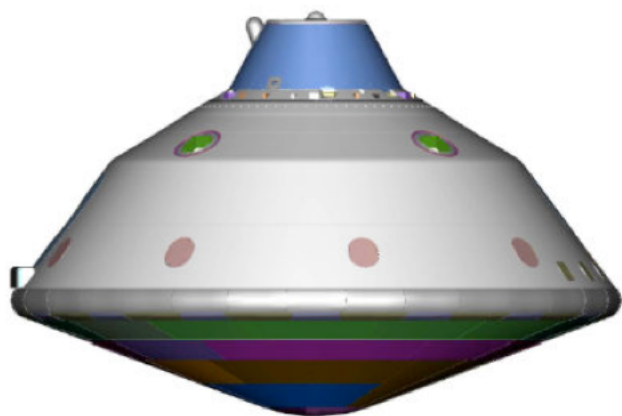
Outline



- MSL EDL overview and MEADS system hardware
- Mars reconstruction history and the value of MEADS
- MEADS system characterization
- Full entry system characterization and reconstruction development



EDL Timeline



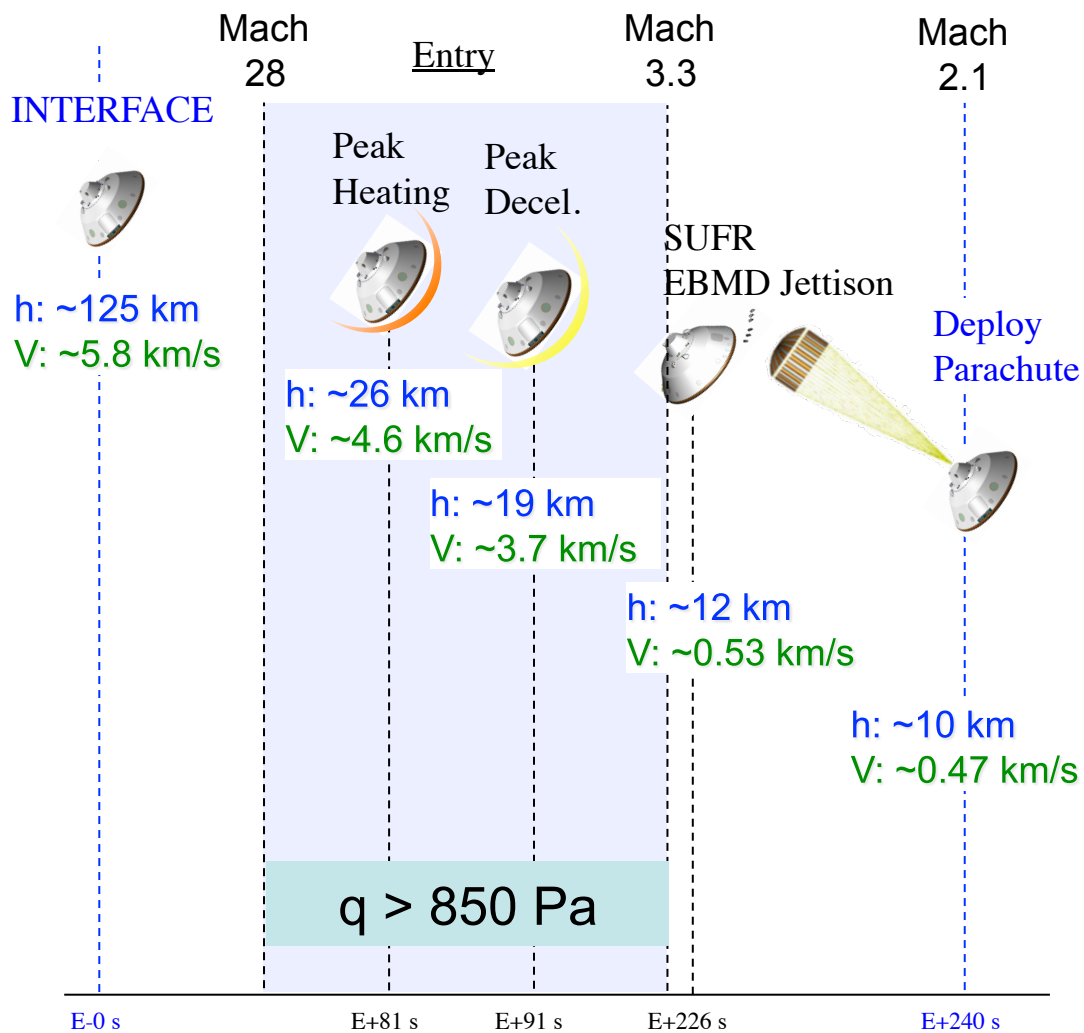
MSL Entry Vehicle

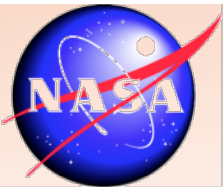
4.5m diameter
70 deg sphere-cone

Entry Mass: 3200kg

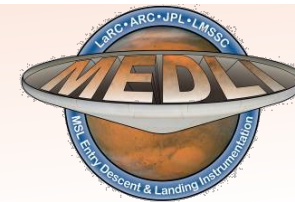
Hypersonic L/D: 0.24

Trim AoA: 17 – 20 deg



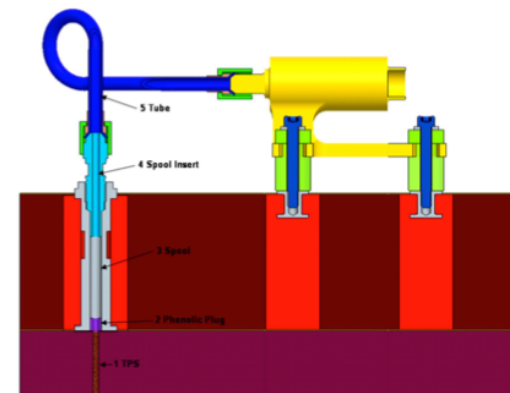
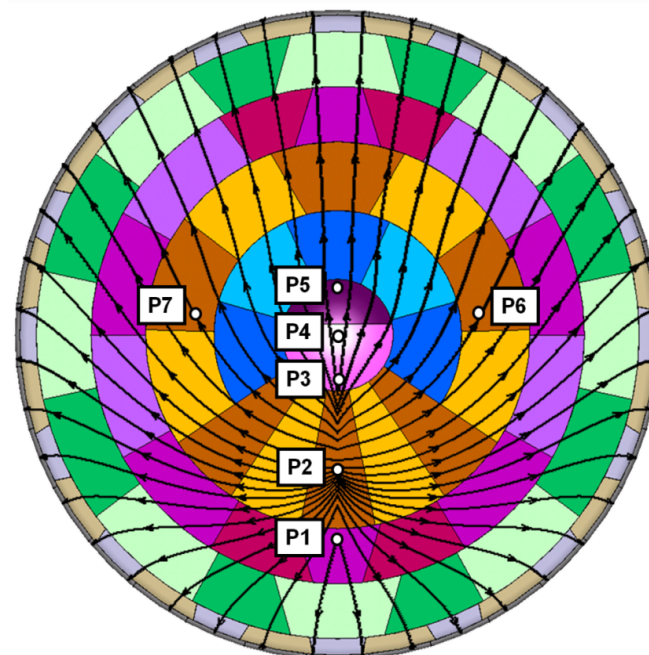


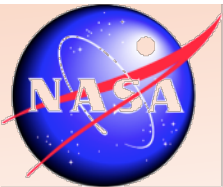
MEDLI MEADS Experiment



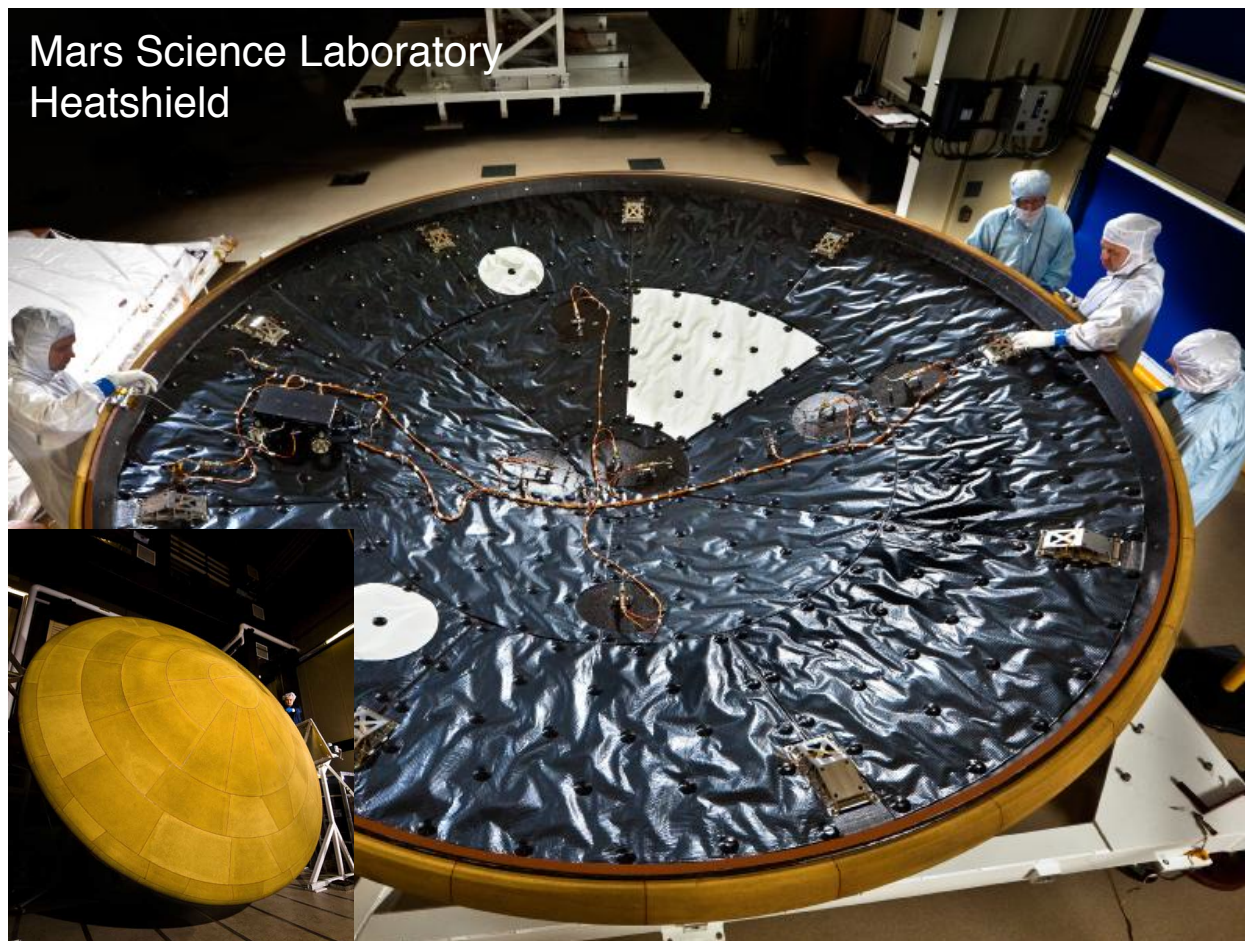
MEADS Pressure Transducers:

- 7 pressure transducers used to determine dynamic pressure, angle of attack and angle of sideslip
- Transducer full-scale: 5 psi (34.5 kPa)
- Data is sampled at 8Hz from entry interface down to heatshield separation
- Each transducer is a minimum of 3" from a tile seam
- Experiment designed to meet measurement specs (q, α, β) at dynamic pressures greater than 850 Pa (0.123 psi)
- Transducer heads are located near pressure taps. Electronics for all transducers are located within dedicated Sensor Support Electronics (SSE) box mounted on heatshield interior





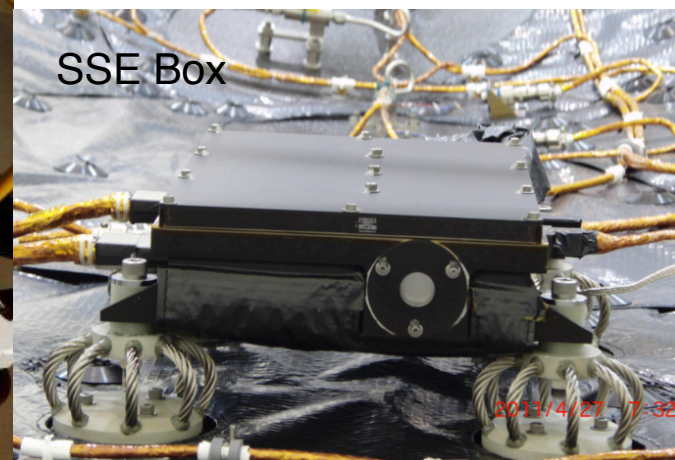
Flight Hardware



Mars Science Laboratory
Heatshield



STI Transducer



SSE Box



MEADS Data Products: Separate Drag Coefficient from Dynamic Pressure

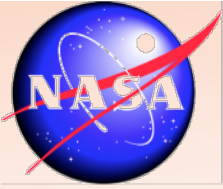


What is the science/engineering data return from MEADS?

- IMU measurements with predicted aerodynamic and atmospheric data have been used to reconstruct Mars entry trajectories for all recent missions.
- Onboard IMU measurements reconstruct inertial velocities and the path through Mars' atmosphere.
- Accelerometers provide an estimate of drag, but dynamic pressure cannot be separated from drag coefficient

$$\frac{1}{2}\rho_{\infty}V_{\infty}^2C_DS_{ref} = m_{ev}a_x \quad \Rightarrow \quad \left(\frac{1}{2}\rho_{\infty}V_{\infty}^2C_D\right) = \frac{m_{ev}a_x}{S_{ref}}$$

- Density can be estimated to the accuracy of preflight drag predictions, or the drag coefficients can be estimated to the accuracy of modeled or remotely measured density profiles.
- MEADS will measure stagnation pressure which closely correlates to dynamic pressure, thus identifying both the density column and drag coefficient history.



Dynamic Pressure Accuracy

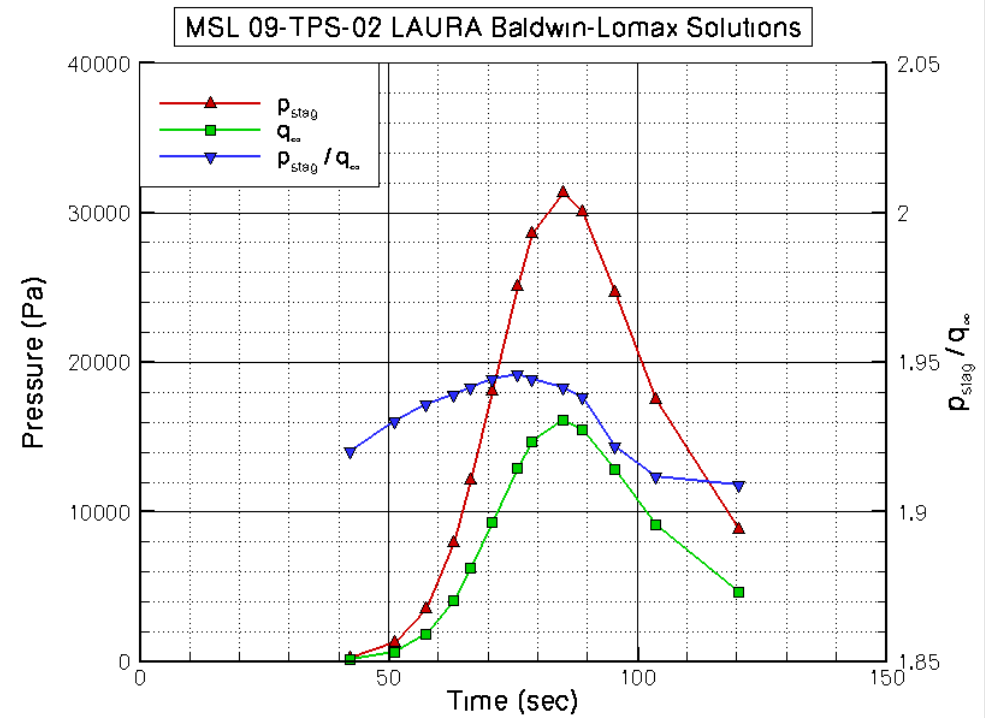


MEADS will measure the dynamic pressure history during entry

Rearranging the Rayleigh Pitot Equation:

$$q_{\infty} = p_{o,2} \left(\frac{\gamma}{\gamma + 1} \right) \left(\frac{4\gamma}{(\gamma + 1)^2} - \frac{2(\gamma - 1)\gamma RT_{\infty}}{(\gamma + 1)^2 V_{\infty}^2} \right)^{\frac{1}{\gamma - 1}}$$

- Dynamic pressure is primarily a function of stagnation pressure and γ .
- At hypersonic speeds, the ratio of specific heats is not constant. γ is the significant source of error.
- γ determined from non-equilibrium, chemically reacting CFD predictions, experiment, and theory





MEADS Data Products: Independent Measure of Wind-Relative Vehicle Attitude



What is the science/engineering data return from MEADS?

- IMU reconstruction can determine the capsule attitude relative to the inertial velocity vector. This approximates angle-of-attack and sideslip but does not reflect wind components.
- The ratio of transverse to axial accelerometer readings can be matched to preflight aerodynamic predictions to determine α and β . For blunt bodies this approach is prone to errors from CFD uncertainties and IMU alignment.

$$\left(\frac{a_z}{a_x} \right)_{measured} = \left(\frac{C_N}{C_A} \right)_{fn(\alpha)}$$

- MEADS pressure measurements form a Flush Air Data System (FADS) which are compared to CFD and experiment-based pressure models, yielding more accurate and robust α and β measurements.
- Ultimately, IMU and MEADS measurements will be combined to yield a trajectory reconstruction superior to versions obtained independently



MEADS Uncertainty Analysis



The accuracy characterization of the MEADS system was deliberately separated into two segments:

1 Hardware Accuracy and Contribution to Reconstruction Uncertainty

Characterize the relative error contributions from all known sources of error using perfect pressure and IMU information.

This phase ensures the physical hardware is performing to spec and will determine the uncertainty contributions of the pressure system only.

2 Full System Uncertainty Analysis and Reconstruction Development

Add the remaining sources of error used to determine dynamic pressure and angles of attack and sideslip to determine the expected accuracy of the MEADS experiment.

The uncertainties using other onboard instrumentation is also assessed to determine how all the data sources will be used for the final trajectory reconstruction.



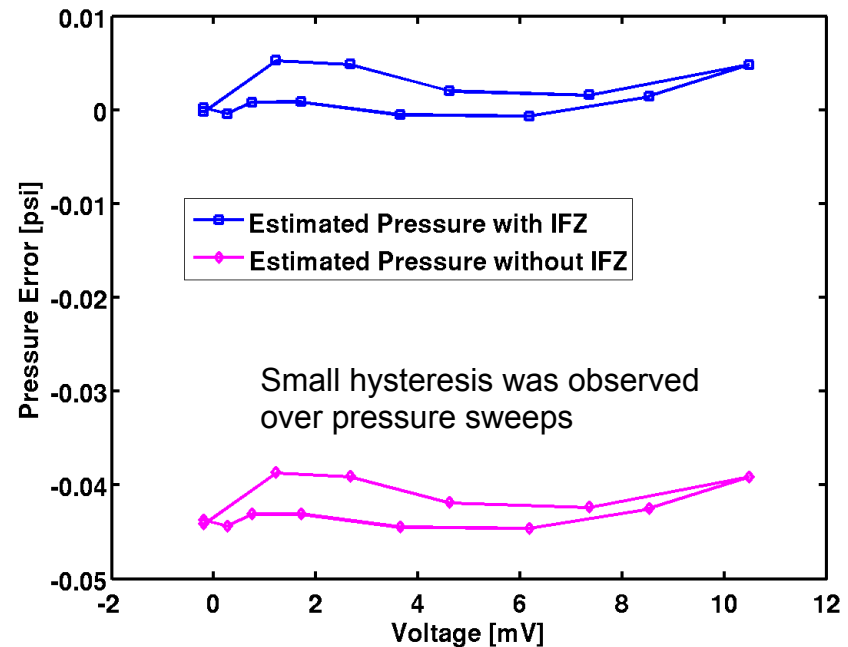
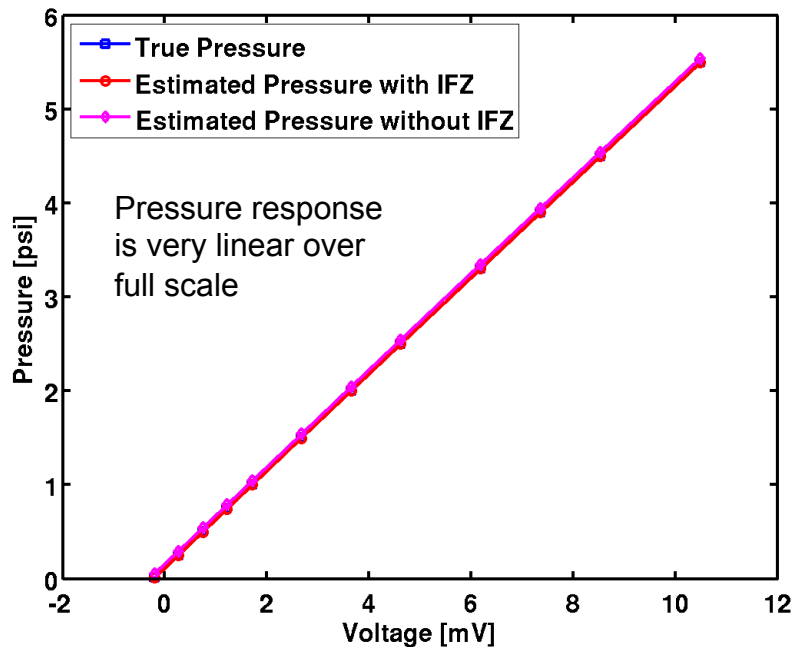
Transducer Calibration and Effect of In-Flight Zero

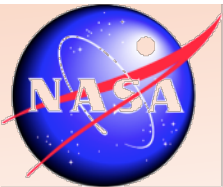


MSL will have vacuum reading prior to entry interface. This in-flight zero effectively eliminates the intercept error for each transducer

EXAMPLE:

- Data points from temperature setpoint T4
 - Transducer ~ -82.9 deg C
 - SSE ~ 9.7 deg C
- In-flight zero calculated from average of first and last pressure point

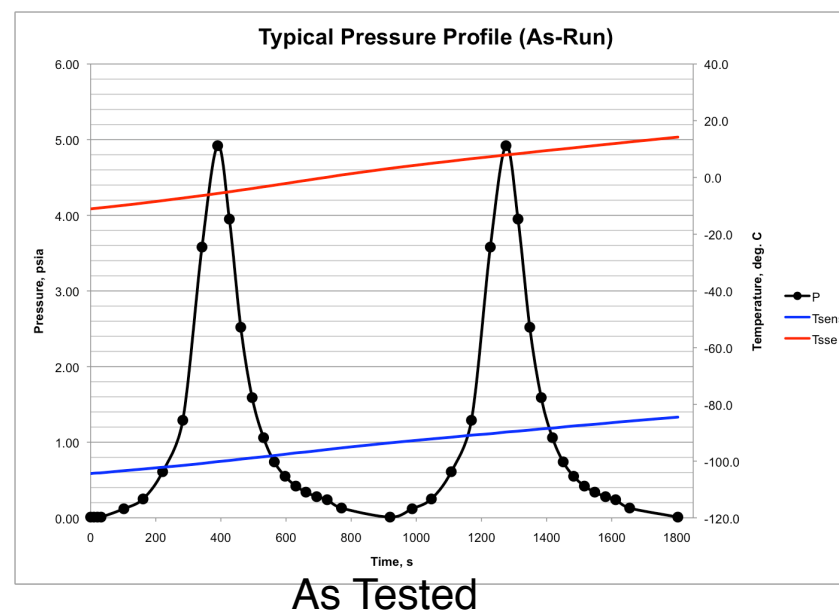
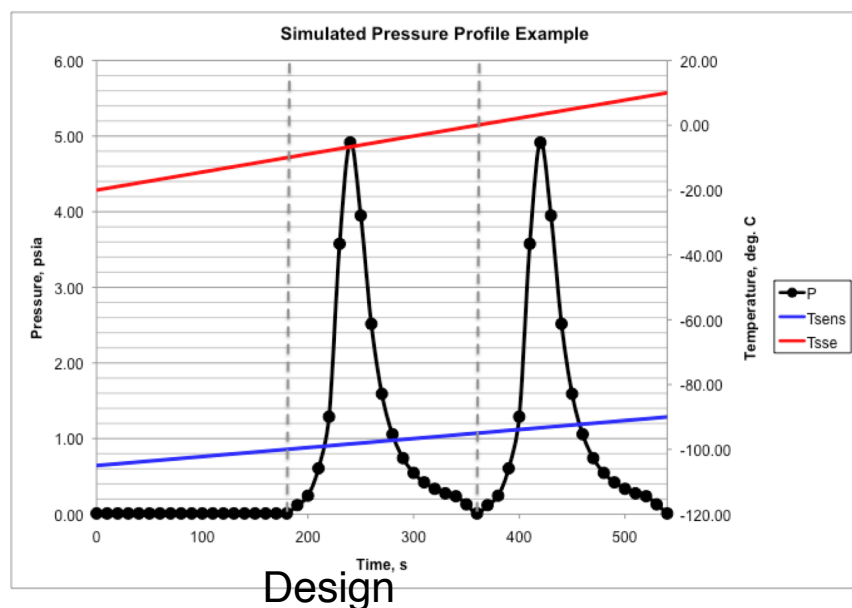


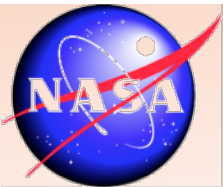


Simulated Entry Profiles

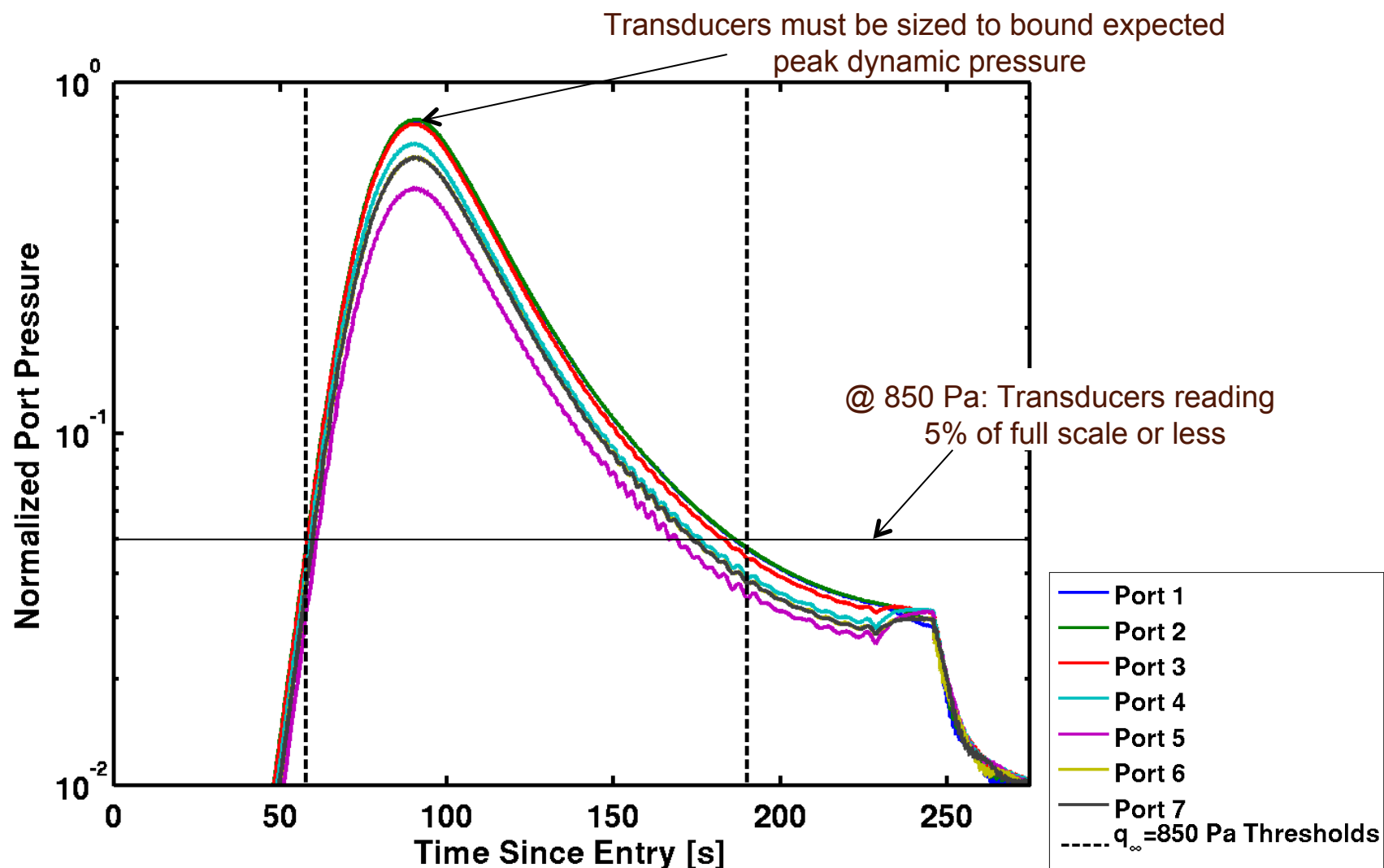


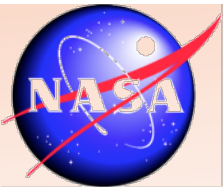
- Objective for simulated entry profiles were to obtain pressure variations that mimic entry conditions with SSE and transducer temperature ramps that conservatively bound the expected thermal response during entry.
- Long dwell at low pressures to provide “in-flight zero” data
- In practice, pressures could not be controlled quickly enough to match entry profile. Simulated pressure pulse is useful but not completely flight-like





Pressure Normalized by Full Scale

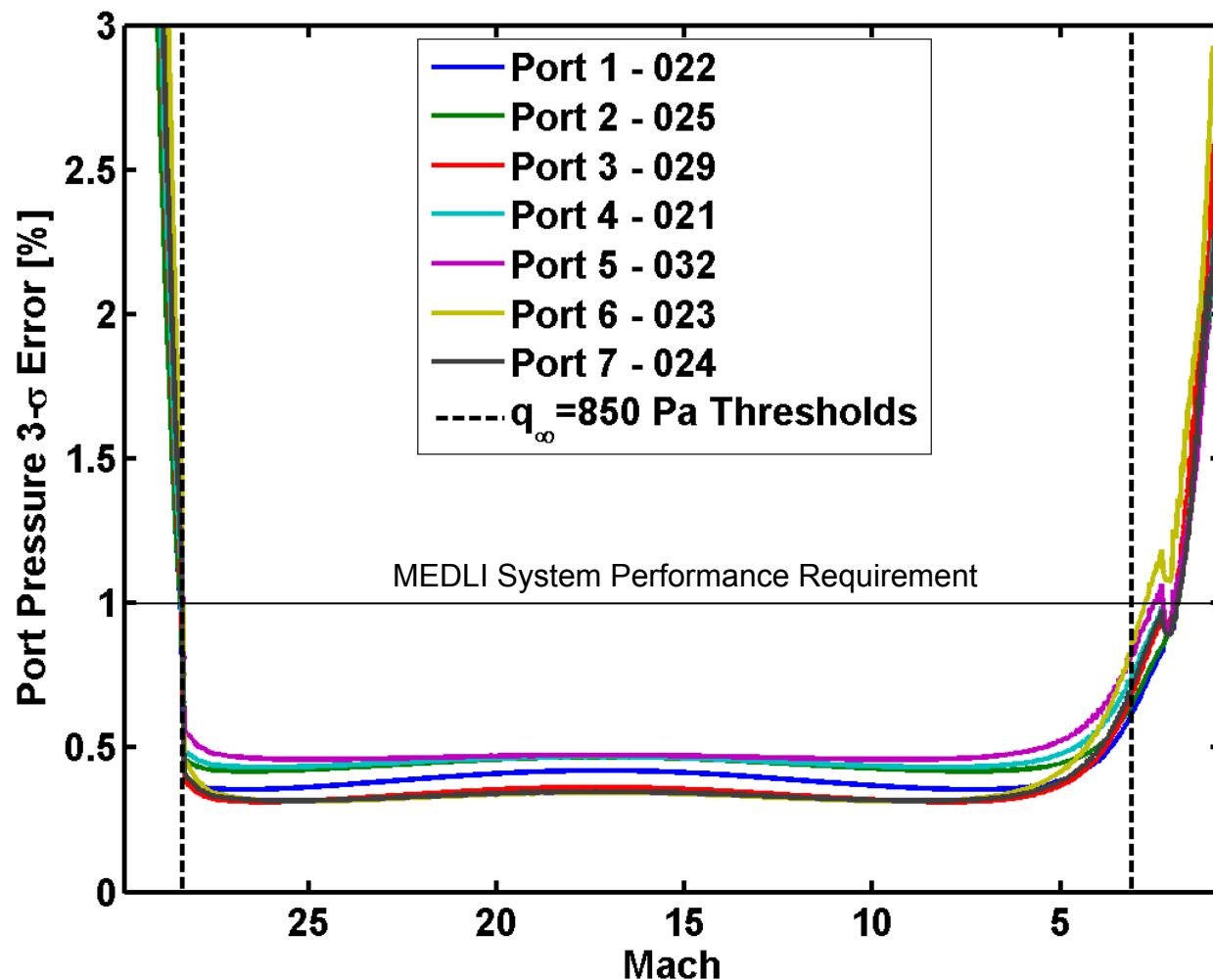




Pressure Measurement: Total System Error vs. Mach (% reading)



Flight System



Sources of error:

- Transducer Calibration
- SSE
- Installation/location
- Time latency



MEADS System Uncertainty Analysis

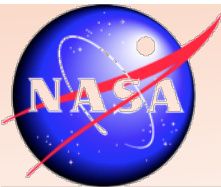


Objective: Demonstrate MEADS pressure accuracy is sufficient to measure dynamic pressure and attitude

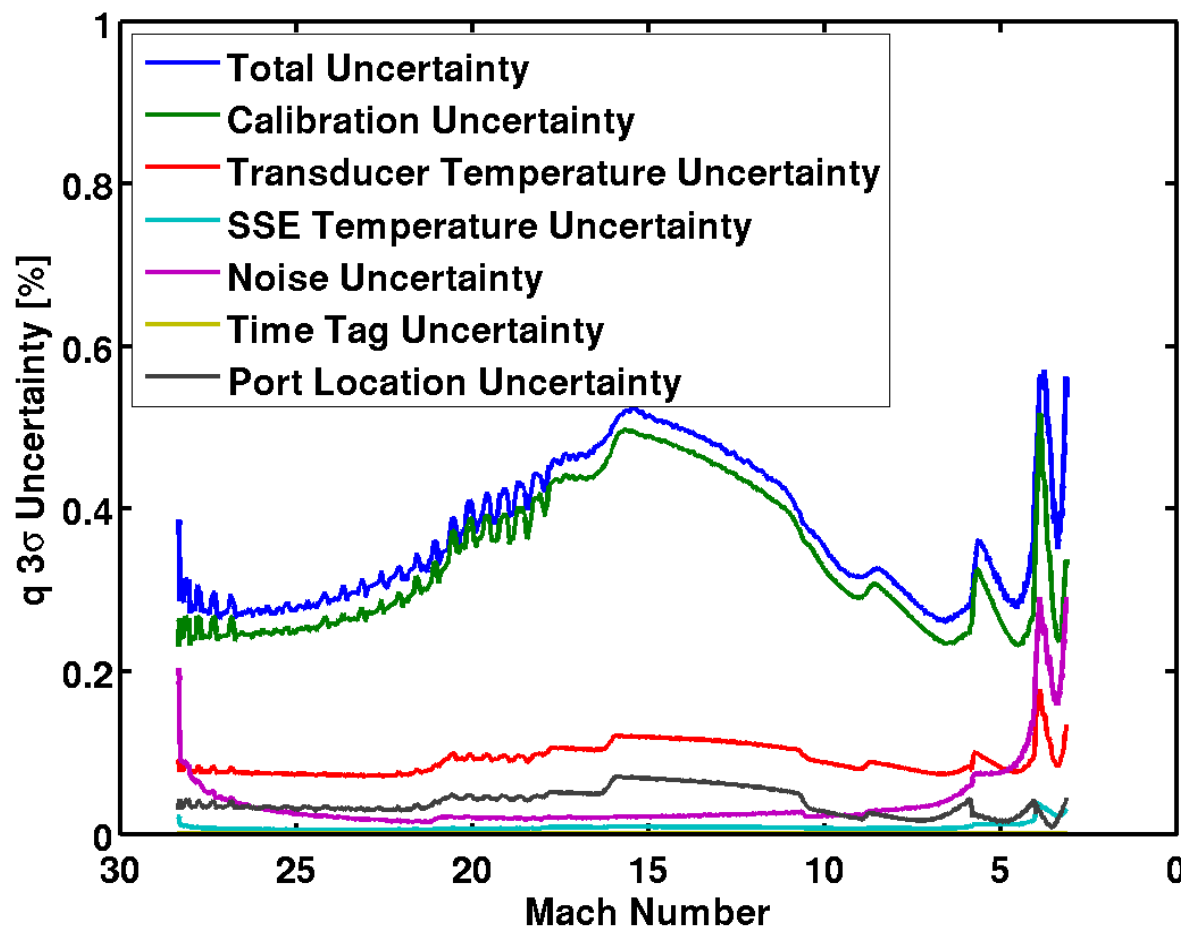
Monte Carlo analysis used to determine the overall uncertainties and contributions to identified sources of error

- Calibration Uncertainties
- Temperature uncertainties
- Initial temperatures of transducers and SSE
- SSE noise, quantization, and time stamp errors
- Port location knowledge

Sources of error not directly related to MEADS hardware were deliberately **not** assessed. For flight certification, we are interested the MEADS contribution to error only.

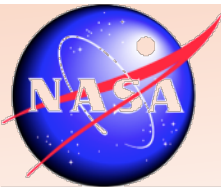


MEADS System: Dynamic Pressure Uncertainty

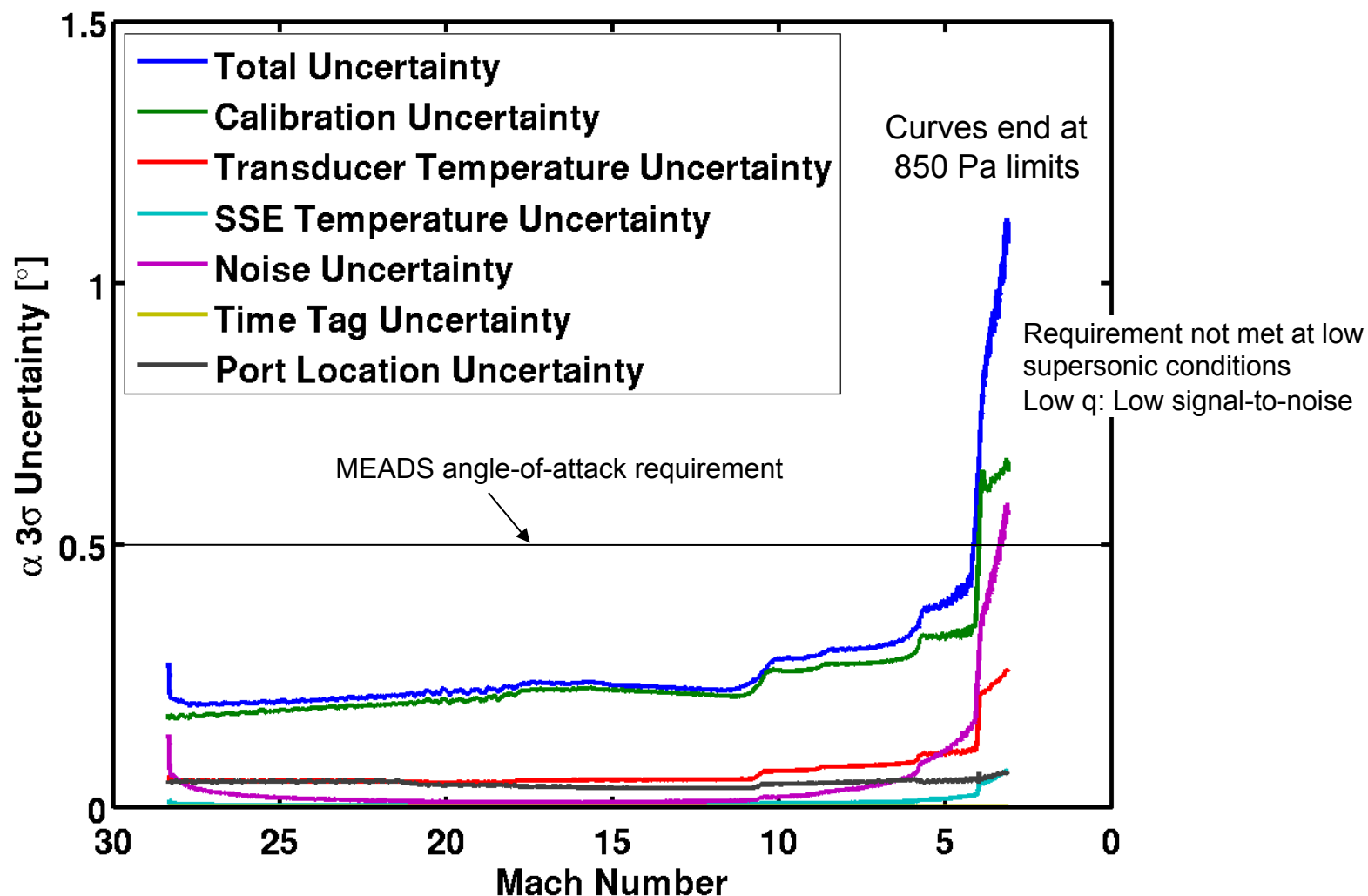


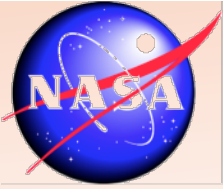
MEADS Dynamic Pressure
requirement: $\pm 2\%$

Determining dynamic pressure is the key to separating aerodynamic uncertainties from atmosphere uncertainties.
e.g. separates density from drag coefficient from measured deceleration

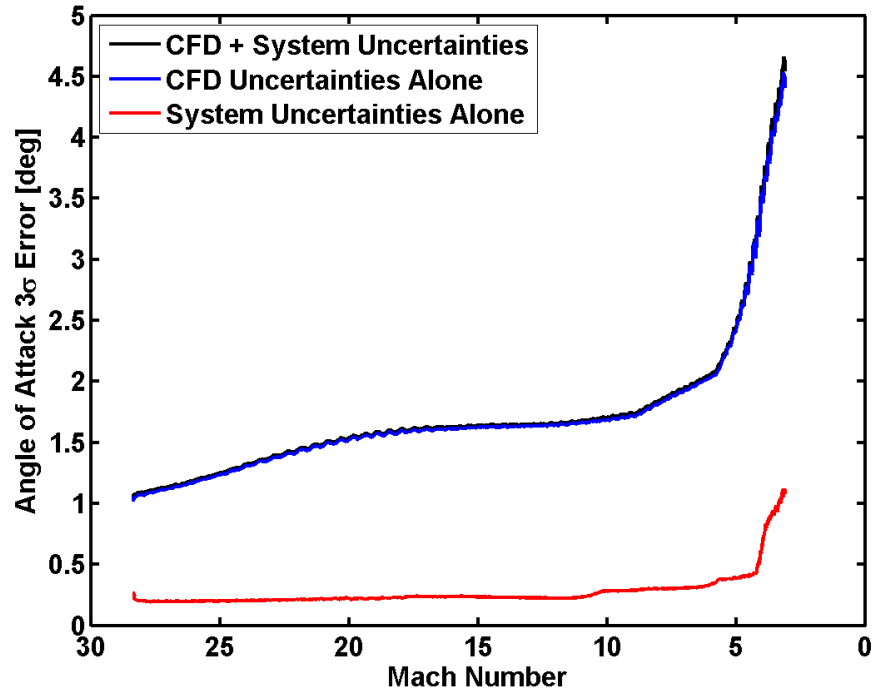
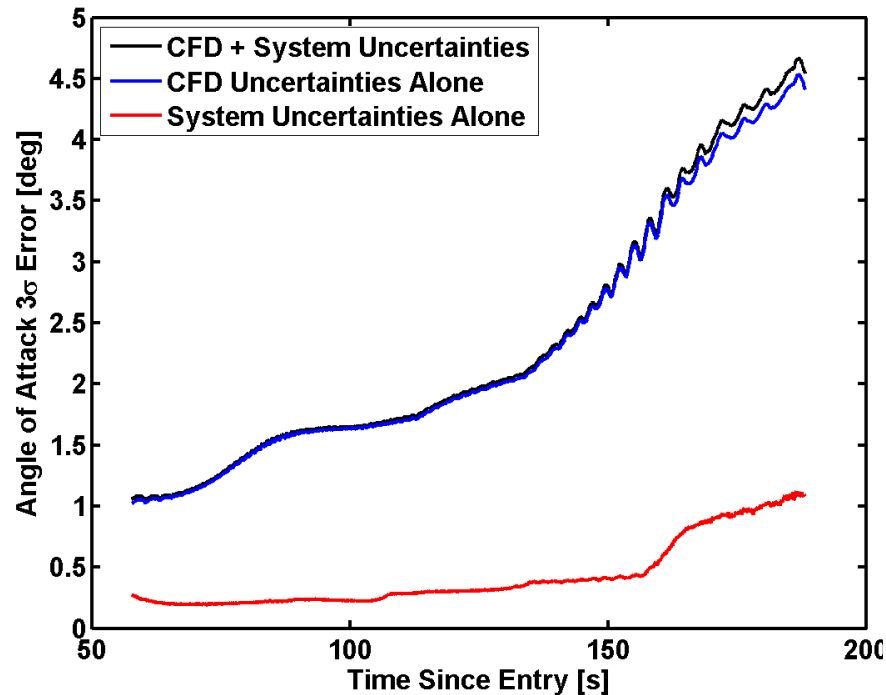


MEADS System: Angle of Attack Uncertainty





Comparison with CFD Uncertainties



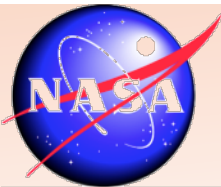
Current pressure uncertainty model applied to CFD data used for entry parameter identification overwhelms contributions due to MEADS measurement system.

This model is expected to be improved with wind tunnel testing. CFD uncertainty quantification is not well understood, but is a major contributor to total reconstruction uncertainty for angles of attack and sideslip.



Total System Reconstruction Accuracy

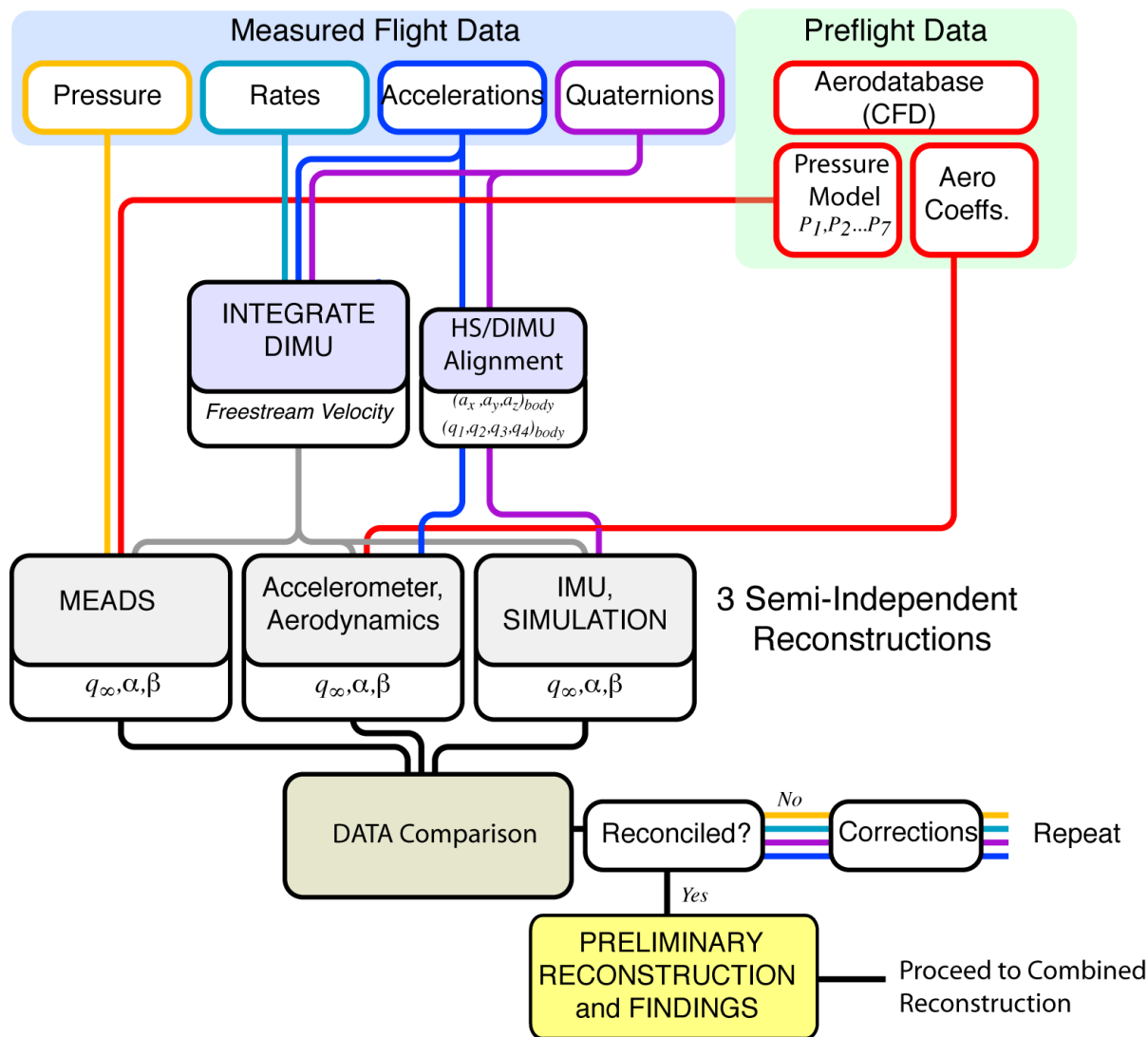
MEADS will be combined with IMU measurement for final trajectory reconstruction. What is the overall accuracy using all available information?



Reconstruction Approach

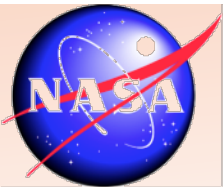


MSL/MEADS Data Reduction Flow Chart

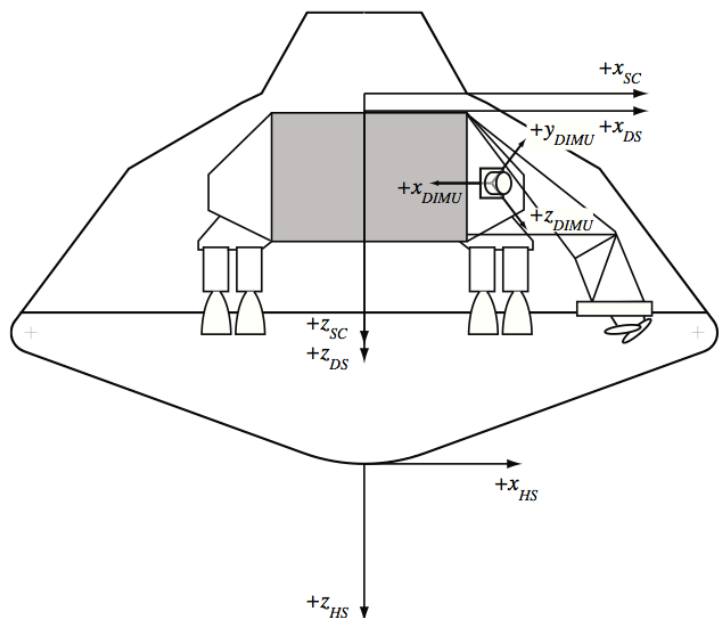


As with MEADS
Uncertainty analysis of all
data sources is being done
currently

Comparing independent
reconstructions with
uncertainties will help
identify suspect data



Example: IMU Misalignment



$$\begin{pmatrix} \frac{a_z}{a_x} \end{pmatrix}_{measured} = \begin{pmatrix} \frac{C_N}{C_A} \end{pmatrix} fn(\alpha)$$

$$\Delta\alpha_T = -\frac{C_A}{C_{N_{\alpha T}}} \Delta\epsilon$$

The MSL IMU installation requirement (1mrad) was driven by the accuracy required to fly a guided entry.

To use the IMU with the aeroshell as an attitude measurement instrument requires additional “calibration.” α, β error can be an order of magnitude greater than IMU orientation error.

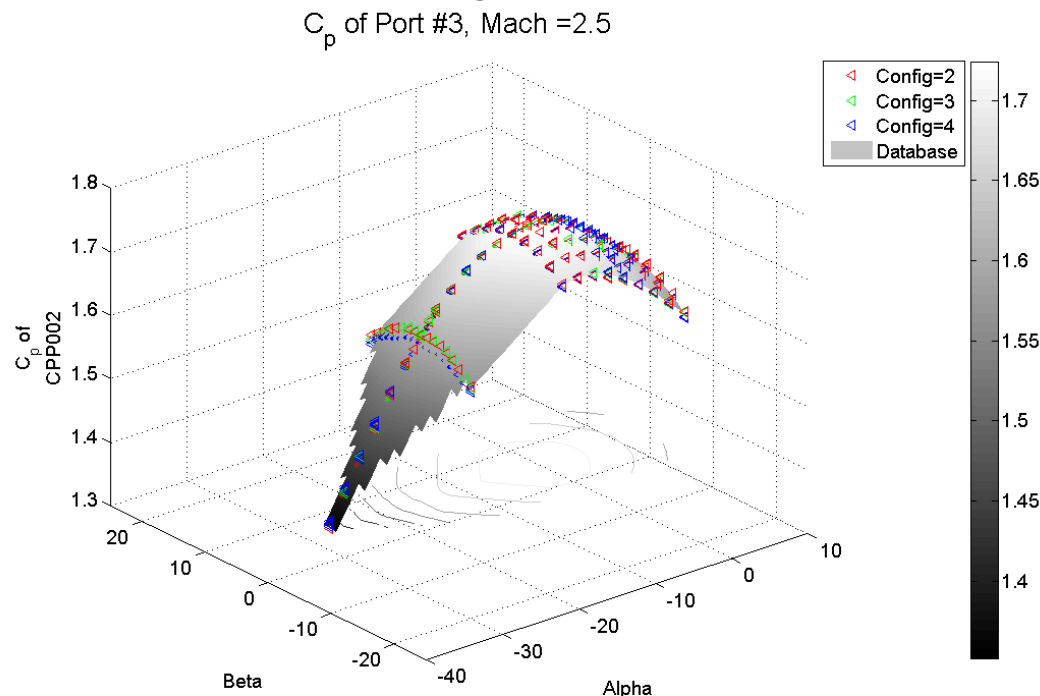
MEDLI-requested, IMU-HS alignment measurements added to ATLO process



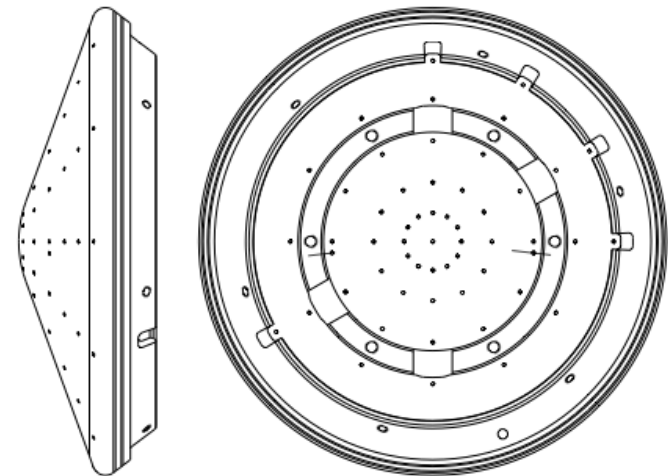
CFD Uncertainty and Calibration

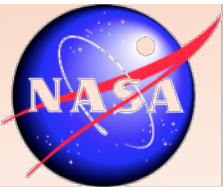


- Largest contributor to MEADS uncertainties is the CFD model used to convert port pressures to angles and dynamic pressure.
- CFD uncertainties are not well quantified in general. The local uncertainties (at the MEADS ports) is a new question to the CFD community.
- MEDLI is anchoring CFD codes to supersonic and hypersonic wind tunnel tests.

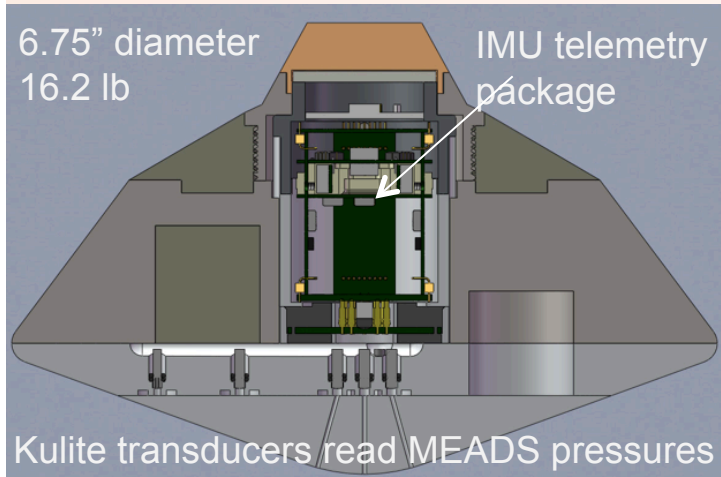


Supersonic model: 90 ports
12 instances of the MEADS ports,
clocked around the model





Aberdeen Proving Grounds Ballistic Range Test

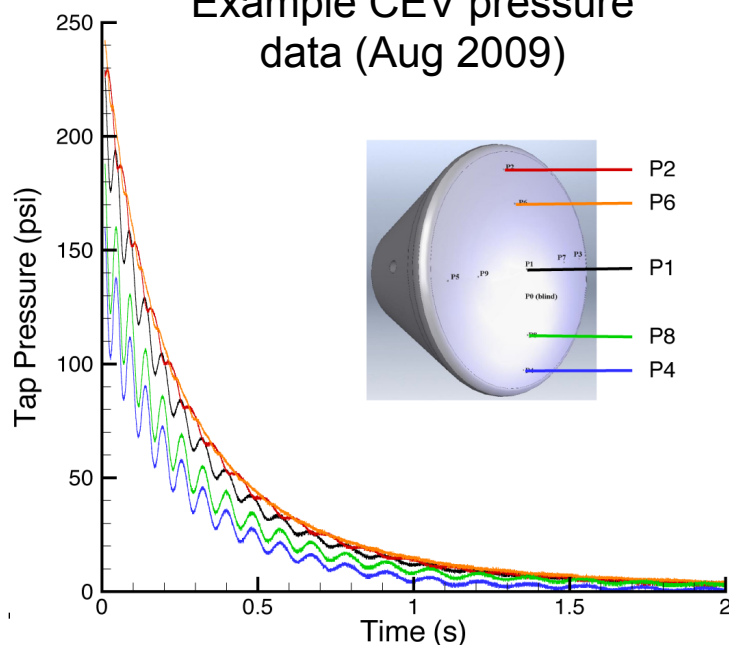


This year, a series of ballistic range tests will be conducted to demonstrate and refine the reconstruction approaches developed for MEDLI.

Each model will telemeter onboard pressure, accelerometer, rate and magnetometer data, and will be tracked by radar.

- Testing in air will make wind tunnel data directly relevant (no CO₂ vs Air uncertainty)
- RADAR tracking provides inertial trajectory path “truth” to within meters.
- MET data provides Mach measurements with accuracy of RADAR velocity measurements.

Example CEV pressure data (Aug 2009)



Aberdeen Proving Grounds 7” Gun

Initial Mach: ~3.6

~10kHz data rate

~10s flight data



IPPW-8



Summary



MEADS Flight Hardware was successfully calibrated and characterized for flight Aboard the Mars Science Laboratory Entry Vehicle

- MEADS system meets project uncertainty requirements for measuring pressure and orientation
- Individual sources of error have been identified and their relative contributions determined
- The MEADS hardware will measure entry pressures very accurately
- Dynamic pressure will be measured and will reduce errors on drag and density predictions for future flights

The determination of angle-of-attack and sideslip is reliant on additional data:

- CFD uncertainties are the big challenge for accurate attitude measurement
- No experimental facility exists for Mach > 10. Essentially no useful CO2 facilities either
- Work continues to characterize all sources of error
- Interpreting all onboard measurements in the context of reconstruction is key to identifying suspect data and for balancing all data sources in final reconstruction.

**MEADS hardware has been installed and is sitting in storage at KSC
The MSL launch window opens on November 25, 2011**